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Integrated modelling of corrosion-induced deterioration in reinforced concrete structures

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Summary

An integrated finite element based modelling approach is presented, which allows for fully coupled simulation of reinforcement corrosion and corrosion-induced concrete damage. While a finite element method (FEM) based corrosion model was used to describe electrochemical processes at the reinforcement surface, a FEM based mechanical model was used to simulate corrosion-induced concrete damage. Both FEM models were fully coupled, i.e. information, such as corrosion current density, damage state of concrete cover, etc., were constantly exchanged between the models. To demonstrate the potential use of the modelling approach, a numerical example is presented which illustrates full coupling of formation of corrosion cells, propagation of corrosion, and subsequent development of corrosion-induced concrete damage.

1 Introduction

Deterioration of the civil infrastructure (bridges, tunnels, roads, and buildings) together with increasing functional requirements (e.g. traffic load and intensity) present major challenges to society in most developed countries. A major part of the infrastructure is build from concrete and costs for maintenance, renovation, and renewing are growing and by now taking up a major part of concrete structure investments. While engineering tools and methods are well developed for the structural design of new structures, tools for assessing current and predicting the future condition of existing reinforced concrete structures are less advanced. Present prediction tools are largely empirical, see e.g. [1,2], and thus limited in their ability to predict the performance of new material, structural, or maintenance solutions. A primary reason for the lack of reliable modelling tools is that deterioration mechanisms are highly complex, involve numerous coupled physical phenomena, must be evaluated across a range of scales, and often cut across several academic disciplines.

In this paper a cross disciplinary modelling approach is presented that deals with chloride-induced reinforcement corrosion (initiation and propagation) and corrosion-induced concrete cracking in reinforced concrete.

2 Integrated modelling approach

The basic concept of the developed integrated modelling approach is illustrated in Fig. 1. It combines coupled transport of heat and matter, reinforcement corrosion, and corrosion-induced concrete damage. Initially the transport and distribution of heat and matter is solved along with the corrosion potential and corrosion current density. Information on the distribution of heat, matter, corrosion potential, and corrosion current density are subsequently used to simulate corrosion-induced concrete damage, i.e. corrosion-induced deformations and cracks. Finally, the influence of corrosion-induced deformations and cracks is taken into account in the simulation of heat, matter, and reinforcement corrosion.

2.1 Modelling reinforcement corrosion

To model initiation and propagation of reinforcement corrosion in concrete structures a physio-chemical corrosion model was established. Two physical laws were used to describe the electrochemical processes and determine the corrosion rate of steel embedded in concrete. The first one is Laplace's equation (see Fig. 1) describing the potential distribution in concrete assuming electrical charge conservation and isotropic conductivity. The second is Ohm's law (see Fig. 1), which was used to determine the corrosion current density if the potential distribution and resistivity of the electrolyte are known [3]. Kinetics of the electrochemical processes are described by anodic and cathodic polarisation curves (see Fig. 1), which comprised activation and concentration polarisation. The electrochemical processes, i.e. the corrosion model, are further coupled with transport mechanisms to account for the impact of temperature, relative humidity, and oxygen on the reinforcement corrosion process. To link initiation, i.e. the formation of anodic regions, and propagation of reinforcement corrosion a conditional statement was defined along the reinforcement surface, which comprises the definition of a critical chloride threshold. When the critical chloride concentration for an element along the reinforcement surface is reached, the element will become anodic while the rest of the reinforcement surface will stay cathodic. More detailed information on the applied modelling techniques to describe the transport of heat and matter and reinforcement corrosion can be found in [4,5] and [6,7], respectively.

2.2 Modelling corrosion-induced concrete damage

A thermal analogy was used (see Fig.1) to model corrosion-induced concrete damage due to the expansive nature of solid corrosion products. The corrosion-induced damage was described by a discrete cracking approach (see Fig.1 Eq. 1) in which the tension softening was modelled by multi-linear softening relations (see Fig.1 Eq. 2) adopted from [8]. The simulated corrosion-induced damage included cracking of the cementitious matrix (mode I fracture) and delamination at the steel-matrix interface (combined mode I and II fracture), both considered along predefined crack paths.

For the determination of the corroded reinforcement section, Faraday's law was used (see Fig. 1 Eq. 3) relating the thickness reduction per time unit to the corrosion current density (predicted by the corrosion model). Assuming a constant coefficient of thermal expansion, α_{fict} , the applied temperature increment, ΔT , represented the type of solid corrosion product (see Fig. 1 Eq. 4). Formation of soluble corrosion products, such as iron-chloride-complexes was not included in the modelling approach. The model further accounted for non-uniform formation of corrosion products along the circumference of the reinforcement as well as penetration of corrosion products into the available pore space of the surrounding cementitious matrix, referred to as corrosion accommodating region (CAR). The CAR describes a region of concrete around the reinforcement that can accommodate corrosion products delaying stress development in the concrete. The CAR has a major influence on the predicted time-to-crack initiation and crack propagation behaviour [9,10]. The accommodation of corrosion products in the CAR was accounted for in the model by an adjusted temperature increment, ΔT_{CAR} (see Fig.1 Eq. 5). For the description of ΔT_{CAR} Eq.6 and Eq.7 (see Fig. 1) were used, which are based on experimental observations presented in [11,12].

While additional information on the general modelling approach for corrosion-induced concrete damage can be found in [13,14], more detailed information on the implementation of penetration of corrosion products and non-uniform formation of corrosion products in the modelling scheme are given in [11,12] and [15,16], respectively.

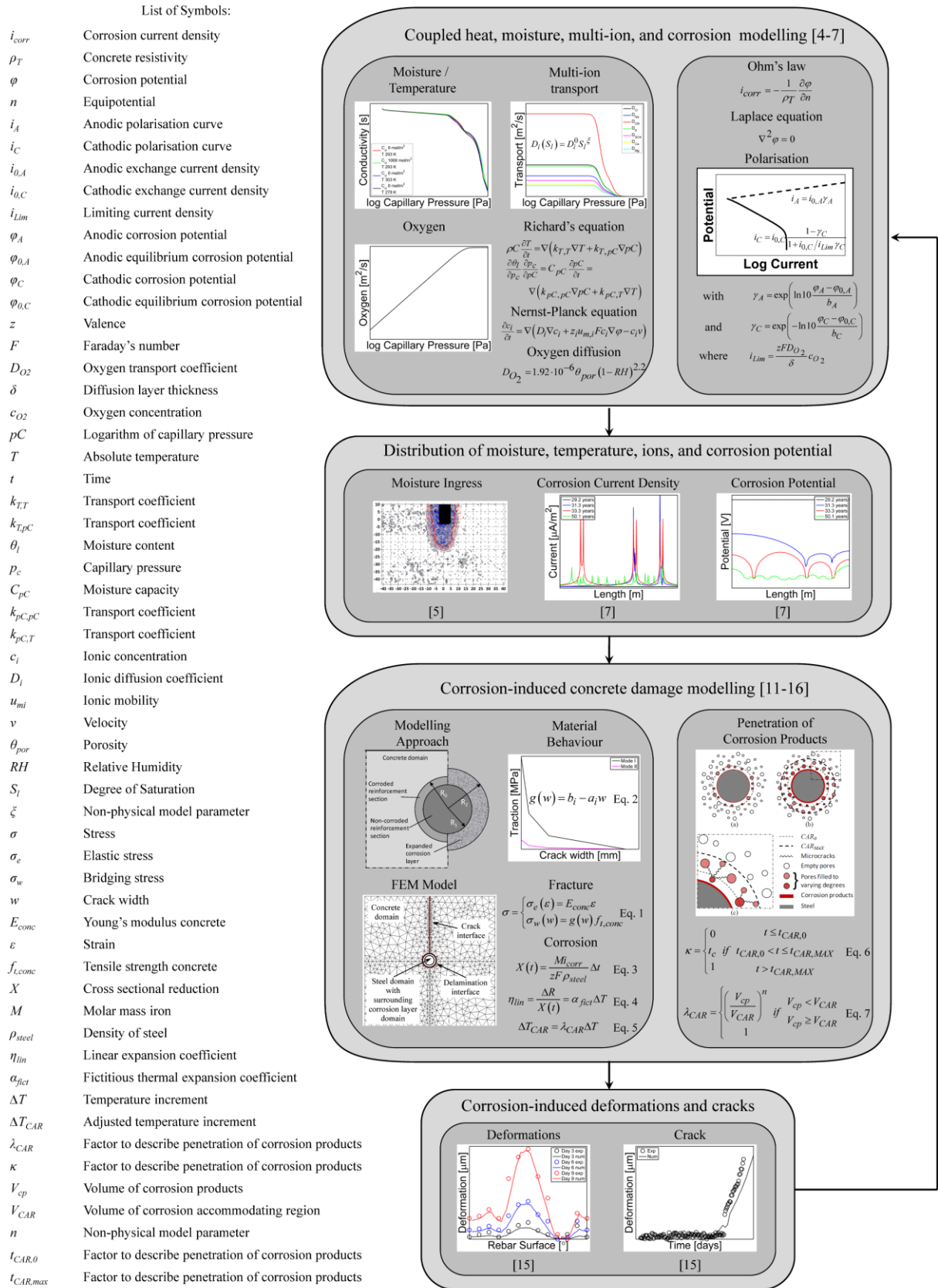


Figure 1: Concept of integrate modelling approach including transport of heat and matter, reinforcement corrosion, and corrosion-induced concrete damage.

3 Numerical example and selected results

To demonstrate the potential use of the modelling approach, a numerical example is given. In the example, a 2D cross section exposed to a 3% sodium chloride solution is simulated to illustrate fully coupled initiation and propagation of reinforcement corrosion and corrosion-induced damage. While the model geometry and general conventions are given in Fig. 2 (a), selected results are presented in Fig. 2 (b - j). Along the the circumference of the reinforcement, different critical chloride thresholds were defined (see Fig. 2 a) to account for experimentally observed variability, see e.g. [17]. Results of the numerical model comprise among others chloride concentration, potential and current density distribution, and cross sectional reduction around the circumference of the reinforcement (see Fig. 2 b-e) for selected times. From the results presented, it can be seen how anodic areas form along the circumference of the reinforcement at different times as the critical chloride threshold is reached. In addition, the chloride concentration in the concrete cover at a depth of 20 mm from the surface is given in Fig. 2 (f). From the presented results, it can further be seen that the corrosion-induced crack (see Fig. 2 g-j) affects the chloride ingress at later simulation times. Finally, the development of the corrosion-induced damage in the concrete cover is presented in Fig. 2 (g-j) for selected times. It should be noted that although corrosion is initiated after approximately 11 months, the corrosion-induced crack does not reach the concrete surface before approximately 30 months.

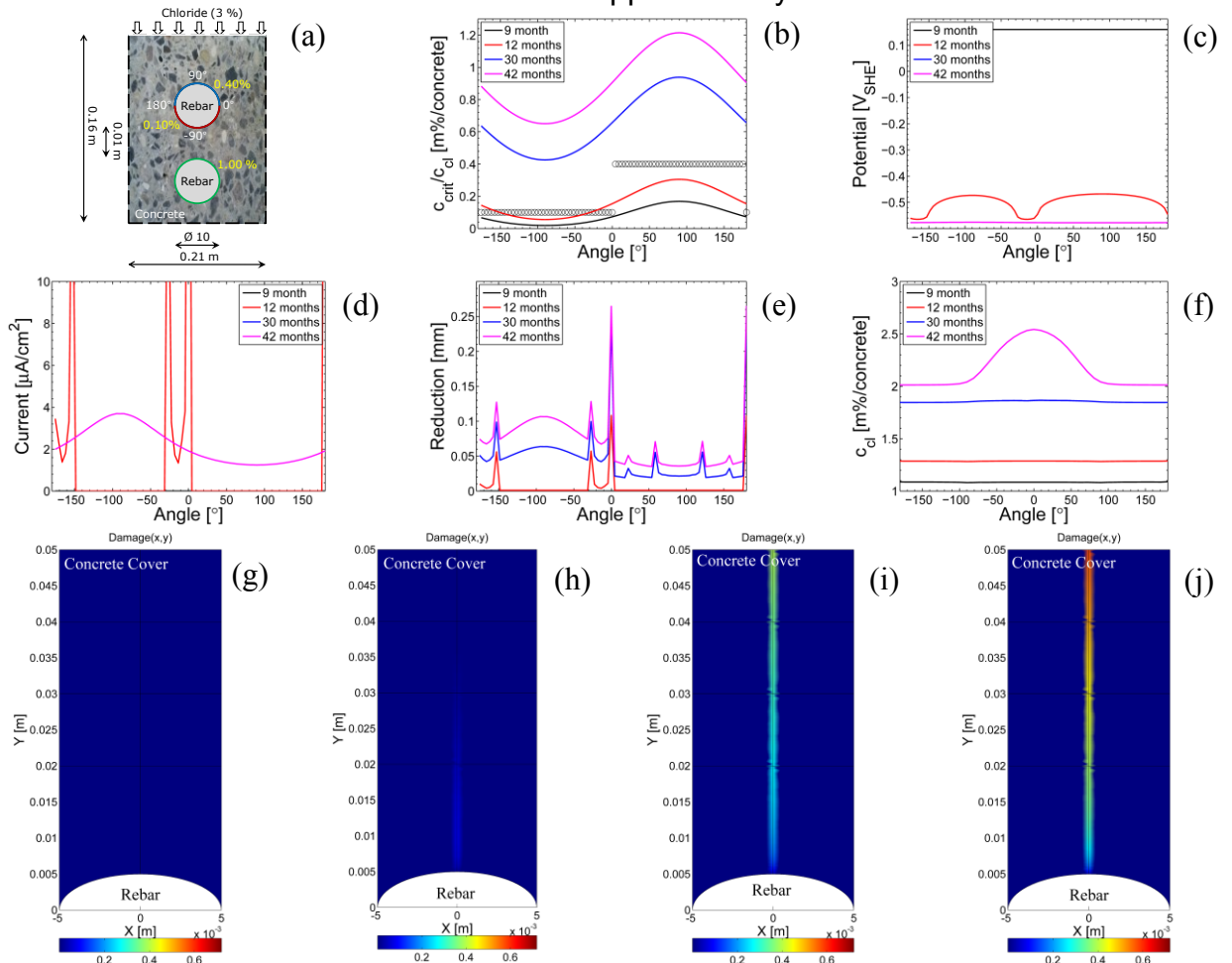


Figure 2: Selected results of integrated modelling approach for the chosen example: model geometry and boundary conditions (a) (please note: not to scale), critical chloride threshold and chloride concentration (b), potential distribution (c), current density distribution (d), and cross sectional reduction (e) along the circumference of the reinforcement as well as chloride concentration in the concrete cover at a depth of 20 mm (f) and corrosion-induced damage in concrete cover (g-j) for 9, 27, 30, and 42 months.

4 Summary and conclusions

An integrated modelling approach was described, which allowed for fully coupled simulation of reinforcement corrosion (initiation and propagation) and corrosion-induced damage in concrete structures. Corrosion was assumed to be initiated once a critical chloride threshold in the vicinity of the reinforcement was reached causing the formation of anodic and cathodic regions. To demonstrate the potential use of the model, an example was given in which a reinforced concrete cross section was exposed to a corrosion-initiating substance under constant temperature and degree of saturation.

Future development of the integrated modelling approach is to include additional corrosion-induced damage phenomena, in particular multiple cracking, in the concrete cover. Furthermore, future studies should focus on the transport properties of cracked concrete in general and the transport of matter in cracks in particular.

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